

# Competition of $\beta$ -delayed protons and $\beta$ -delayed $\gamma$ rays in $^{56}\text{Zn}$ and the exotic $\beta$ -delayed $\gamma$ -proton decay

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## Abstract

Remarkable results have been published recently on the  $\beta$  decay of  $^{56}\text{Zn}$ . In particular, the rare and exotic  $\beta$ -delayed  $\gamma$ -proton emission has been detected for the first time in the  $fp$  shell. Here we focus the discussion on this exotic decay mode and on the observed competition between  $\beta$ -delayed protons and  $\beta$ -delayed  $\gamma$  rays from the Isobaric Analogue State.

## 1 Introduction

Decay spectroscopy is a powerful tool for exploring the structure of nuclei at the drip-lines.  $\beta$ -decay studies, in particular, provide direct access to the absolute values of the Fermi and Gamow-Teller transition strengths,  $B(F)$  and  $B(GT)$ , respectively.

The proton-rich  $^{56}\text{Zn}$  nucleus was observed for the first time at GANIL in 1999 [1].  $^{56}\text{Zn}$  is a weakly-bound nucleus lying very close to the proton drip-line. It has a quite small proton separation energy,  $S_p = 560(140)$  keV [2], and third component of the isospin quantum number  $T_z = -2$ .

The first study of the  $\beta$  decay of  $^{56}\text{Zn}$  was reported in *ref.* [3]. More recently, some interesting results on  $^{56}\text{Zn}$  decay have been reported in *ref.* [4]. Among them the discovery of a rare and exotic decay mode,  $\beta$ -delayed  $\gamma$ -proton decay, which has been seen for the first time in the  $fp$  shell. The consequences of this rare decay sequence for the determination of the Gamow-Teller (GT) strength have also been analyzed.

## 2 The experiment

The experimental study of  $^{56}\text{Zn}$  decay was performed at GANIL in 2010. The experiment used a primary beam of  $^{58}\text{Ni}^{26+}$  to produce  $^{56}\text{Zn}$ . The  $^{58}\text{Ni}$  beam, of  $3.7\text{ }\mu\text{A}$  and accelerated to  $74.5\text{ MeV/nucleon}$ , was fragmented on a natural Ni target,  $200\text{ }\mu\text{m}$  thick. The fragments were selected by the LISE3 separator and implanted into a Double-Sided Silicon Strip Detector (DSSSD). The detection set-up comprised the aforementioned DSSSD detector,  $300\text{ }\mu\text{m}$  thick, a silicon  $\Delta E$  detector located  $28\text{ cm}$  upstream, and four EXOGAM Ge clovers surrounding the DSSSD.

The EXOGAM clovers were used to detect  $\beta$ -delayed  $\gamma$  rays. The purpose of the DSSSD was the detection of both the implanted fragments and the subsequent charged-particle decays, *i.e.*,  $\beta$  particles and  $\beta$ -delayed protons. An implantation event was defined by simultaneous signals in both

the  $\Delta E$  and DSSSD detectors. A decay event was defined by a signal above threshold (50-90 keV) in the DSSSD and no coincident signal in the  $\Delta E$ .

The implanted ions were identified and selected by putting a gate in a two-dimensional identification matrix, obtained by combining the energy loss signal from the  $\Delta E$  detector and the Time-of-Flight. The latter was defined as the time difference between the cyclotron radio-frequency and  $\Delta E$  signal.

### 3 Results on the $\beta$ decay of $^{56}\text{Zn}$

The results on the  $\beta$  decay of  $^{56}\text{Zn}$  [4] are summarized in the decay scheme in *fig. 1* and in table 1, and discussed below.

A half-life of  $T_{1/2} = 32.9(8)$  ms was obtained for  $^{56}\text{Zn}$ , in agreement with *ref.* [3]. To determine  $T_{1/2}$ , a decay-time spectrum has been constructed from the time correlations between a decay event in a given pixel of the

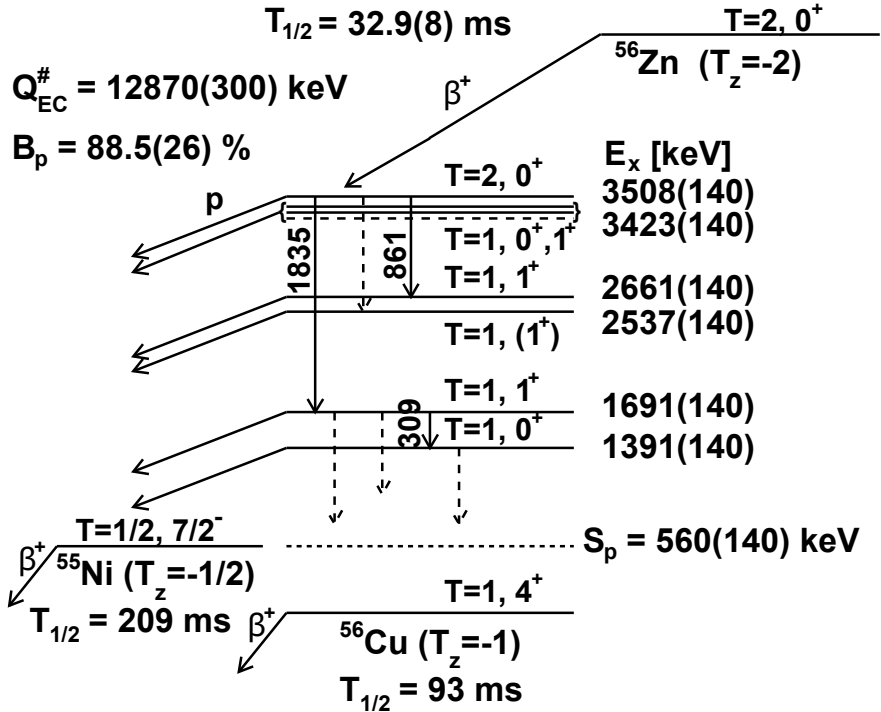


Figure 1: Scheme of the  $\beta$  decay of  $^{56}\text{Zn}$ . The solid lines indicate observed proton or  $\gamma$  transitions, while the dashed lines correspond to transitions observed in the mirror  $^{56}\text{Co}$  nucleus.

DSSSD (with a total of 256 pixels) and any implantation signal that occurred before and after it in the same pixel, satisfying the identification condition required to select  $^{56}\text{Zn}$ .

The analysis of the charged-particle spectrum measured in the DSSSD has provided new spectroscopic information on the energy levels populated in the  $^{56}\text{Cu}$  nucleus, the  $\beta$ -daughter of  $^{56}\text{Zn}$ . These levels are shown in *fig.* 1. The comparison of this level spectrum with that of the mirror  $^{56}\text{Co}$ , obtained by the  $^{56}\text{Fe}(^3\text{He},t)$  charge exchange reaction [5], has been very fruitful.

The analysis of the  $\gamma$  spectrum measured in the EXOGAM clovers and  $\gamma$ -proton coincidences have identified three  $\gamma$  rays at 309, 861 and 1835 keV.

Absolute  $B(F)$  and  $B(GT)$  strengths have been determined (table 1).

Table 1:  $\beta$  feedings, Fermi and Gamow Teller transition strengths to the  $^{56}\text{Cu}$  levels populated in the  $\beta^+$  decay of  $^{56}\text{Zn}$ .

$E_X(\text{keV})$	$I_\beta(\%)$	$B(F)$	$B(GT)$
3508(140)*	43(5)	2.7(5)	
3423(140)	21(1)	1.3(5)	$\leq 0.32$
2661(140)	14(1)		0.34(6)
2537(140)	0		0
1691(140)	22(6)		0.30(9)
1391(140)	0		0

\*Main component of the IAS.

### 3.1 Competition of $\beta$ -delayed protons and $\beta$ -delayed $\gamma$ rays

In the first study of the  $^{56}\text{Zn}$   $\beta$  decay [3], the emission of  $\beta$ -delayed protons was observed but no  $\beta$ -delayed  $\gamma$  rays were seen. This was not a surprise because, in general, in proton-rich nuclei the proton decay is expected to dominate for states well above ( $>1$  MeV) the proton separation energy  $S_p$ . The consequence is that normally the  $\beta$  feeding is directly inferred from the measured intensities of the proton peaks. However, cases where there is a competition between  $\beta$ -delayed proton emission and  $\beta$ -delayed  $\gamma$  de-excitation have also been observed, *e.g.*, in *refs.* [3, 6].

In the  $T_z = -2 \rightarrow -1, \beta^+$  decay of  $^{56}\text{Zn}$  to  $^{56}\text{Cu}$ , the  $^{56}\text{Zn}$  ground state decays with a Fermi transition to its Isobaric Analogue State (IAS) in  $^{56}\text{Cu}$ . It should be noted that the de-excitation of this  $T = 2, J^\pi = 0^+$  IAS via proton decay to the ground state of  $^{55}\text{Ni}$  ( $T = 1/2, J^\pi = 7/2^-$ ) is isospin

forbidden. Therefore the proton emission that we observe can only happen through a  $T = 1$  isospin impurity present in the IAS. Moreover in general, when the proton emission is isospin forbidden, the competitive emission of de-exciting  $\gamma$  rays from the IAS also becomes possible and can be observed even from IAS lying at an excitation energy well above  $S_p$  [3, 6].

The competition between  $\beta$ -delayed protons and  $\gamma$  rays has indeed been observed in  $^{56}\text{Zn}$ . The  $\gamma$  decays represent 56(6)% of the total decays from the 3508 keV IAS. Thus one has to take into account the intensities of both the proton and  $\gamma$  peaks to determine the Fermi strength correctly.

We have also found evidence for the fragmentation of  $B(F)$  due to a strong isospin mixing with a  $0^+$  state at 3423 keV [4], which is important in terms of the mass evaluation [7]. The isospin impurity in the  $^{56}\text{Cu}$  IAS,  $\alpha^2 = 33(10)\%$  (defined as in *ref.* [5]), and the off-diagonal matrix element of the charge-dependent part of the Hamiltonian,  $\langle H_c \rangle = 40(23)$  keV, which is responsible for the isospin mixing of the 3508 keV IAS ( $T = 2$ ,  $J^\pi = 0^+$ ) and the  $0^+$  part of the 3423 keV level ( $T = 1$ ), are similar to the values obtained in the mirror  $^{56}\text{Co}$  nucleus [5].

Thus, the proton decay of the IAS proceeds thanks to the  $T = 1$  component. However, considering the quite large isospin mixing in  $^{56}\text{Cu}$ , the much faster proton decay ( $t_{1/2} \sim 10^{-18}$  s) should dominate on the  $\gamma$  de-excitation ( $t_{1/2} \sim 10^{-14}$  s in the mirror). This is not the case since we are still observing the  $\gamma$  decay of the IAS in competition with it.

The knowledge on the nuclear structure of the three nuclei involved in the decay, *i.e.*,  $^{56}\text{Zn}$ ,  $^{56}\text{Cu}$  and  $^{55}\text{Ni}$ , can provide us with a possible explanation for the hindrance of the proton decay. Shell model calculations are in progress to clarify this point.

### 3.2 The $\beta$ -delayed $\gamma$ -proton decay

Besides the competition between  $\beta$ -delayed proton emission and  $\gamma$  decay, the exotic sequence of  $\beta$ -delayed  $\gamma$ -proton decay has been detected. Indeed  $^{56}\text{Zn}$  does  $\beta$  decay to its IAS in  $^{56}\text{Cu}$  and from there we observe the emission of two  $\gamma$  rays of 861 and 1835 keV, populating the  $^{56}\text{Cu}$  levels at 2661 and 1691 keV, respectively. Due to the low  $S_p$ , these levels are still proton-unbound and thereafter they decay by proton emission. Consequently the rare and exotic  $\beta$ -delayed  $\gamma$ -proton decay has been observed. In addition to these two branches, there is a third case. The 1691 keV level emits a  $\gamma$  ray of 309 keV, going to the level at 1391 keV that is again proton-unbound and then it de-excites by proton emission.

The  $\beta$ -delayed  $\gamma$ -proton decay has been observed here for the first time

in the  $fp$  shell. This rare decay mode was seen only once before, in the  $sd$  shell in  $^{32}\text{Ar}$  [6], but the consequences for the determination of  $B(\text{GT})$  were not addressed in *ref* [6].

The observation of this special decay mode is very important because it does affect the conventional way to determine  $B(\text{GT})$  near the proton drip-line. For a proper determination of  $B(\text{GT})$ , indeed, it is crucial to correct the intensity of the proton transitions for the amount of indirect feeding coming from the  $\gamma$  de-excitation. This finding indicates that it is important to employ  $\gamma$  detectors in such studies. This decay mode is expected to be significant in heavier proton-rich nuclei with  $T_z \leq -3/2$  under study at RIKEN.

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## References

- [1] J. Giovinazzo et al., *Eur. Phys. J. A*, **11** (2001) 247.
- [2] G. Audi et al., *Nucl. Phys. A*, **729** (2003) 1.
- [3] C. Dossat et al., *Nucl. Phys. A*, **792** (2007) 18.
- [4] S.E.A. Orrigo et al., *Phys. Rev. Lett.*, **112** (2014) 222501.
- [5] H. Fujita et al., *Phys. Rev. C*, **88** (2013) 054329.
- [6] M. Bhattacharya et al., *Phys. Rev. C*, **77** (2008) 065503.
- [7] M. MacCormick and G. Audi, *Nucl. Phys. A*, **925** (2014) 61.